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DESIGN SYNTHESIS IN A VIRTUAL ENVIRONMENT

Douglas Maxwell*
Louisiana Tech University
PO Box 10348
Ruston, LA 71272

Rob King
Naval Research Laboratory
4555 Overlook Ave., SW
Washington, DC 20375

Alley Butler**
Louisiana Tech University
PO Box 10348
Ruston, LA 71272

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ABSTRACT

Traditional computer-aided design/engineering (CAD/CAE) is performed in a two-dimensional (2D) environment. Through the CAD system demonstration described in this paper, an alternative to the existing 2D technology for design of products is described. This alternative in which design synthesis is accomplished in a stereoscopic or immersive environment is called the Design Synthesis Virtual Environment or DSVE. Stereoscopic vision permits depth perception and provides perception of "real world" 3D existence. This DSVE technology, as defined in this paper, provides a virtual or immersive environment, computer-generated, but seemingly real.

The authors argue that significant advantages are possible when an immersive environment such as the DSVE is used for design synthesis. In the Design Synthesis Virtual Environment a gestural interface is used, and it is further argued that designers can perform design activities intuitively by using a more natural gestural interface within the design environment, allowing more rapid, efficient actions to create and/or modify product geometry.

As evidence, this paper reports on a demonstration conducted in a Design Synthesis Virtual Environment. Operation of the DSVE is explained, and two example problems are worked. Conclusions are drawn about the

effectiveness of the DSVE and the potential for further development.

INTRODUCTION

Traditional computer-aided design/engineering (CAD/CAE) is performed in a two-dimensional (2D) environment using systems ranging from "low end" personal computers to relatively high-powered computer workstations. The work accomplished in this environment can be rendered in three-dimensions (3D) using perspective view algorithms and appropriate illumination models. However, the display still exists in 2D, because the display device (the CRT screen) typically does not permit immersive viewing. Through the CAD system demonstration described in this paper, an alternative to the existing 2D technology for design of products is described in which design synthesis is accomplished in a fully immersive virtual environment called the Design Synthesis Virtual Environment or DSVE.

Immersion is the sense of presence that is created when the reality of the virtual environment approaches that of the real world. Essential elements for full immersion, as opposed to so-called desktop immersion, are stereoscopic perspective vision, a display that permits the user to look in any direction, passive head and hand tracking, and graphic computing power sufficient to achieve an adequate update rate. In such a system, the user perceives "real world" 3D existence. The

* currently: Naval Research Laboratory, 4555 Overlook Ave., SW, Washington, DC 20375

** corresponding author: 318-257-2357, abutler@engr.latech.edu

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DSVE technology described in this paper not only provides an immersive environment for visualization but for interaction as well.

To date, immersive environments have been used for viewing and analysis of completed designs. Immersive environments are more widely used for training, and for simulation-based design in which geometry has been synthesized by traditional means. However, experience with synthesis in an immersive, tracked stereoscopic environment has been significantly limited. The research reported upon in this paper responds directly to the lack of experience by direct experimentation with synthesis of product geometry in the DSVE.

Immersive virtual reality design systems hold the promise of significant savings in costs and time-to-market for new part designs. By coupling design and prototype activities, practitioners diminish designer effort and time on task while holding the promise of better decision-making and improved design solutions.

The creation of a virtual reality based application such as DSVE exposes engineers to an entirely new paradigm for product design. Rather than using abstract algorithms for solid modeling of products, a designer performs design activities more intuitively in a virtual environment. It is argued that the use of gestures and hand movements provides a more natural interface with the design environment, allowing a more rapid, efficient set of actions to create and/or modify product geometry.

Accordingly, the goal of the research reported upon in this paper is to demonstrate application of the DSVE to accomplish design synthesis of complex mechanical systems such as ships and aircraft. The fundamental premise of this research involves the use of tracked, stereoscopic perspective vision for viewing and interacting with an engineering design environment, the DSVE. Additionally, gestural interfaces are used to provide an improved means of interaction. The expectation is that the DSVE which uses gestural interfaces offers the designer significantly improved opportunities for efficient interaction with the product being designed. The DSVE also provides stereoscopic perspective vision, an advantage in design tasks by engineers.

In describing this research project, this paper begins with a review of the literature to provide context. The hardware and software used to operate the DSVE are discussed next. An overview of DSVE operation is provided, and the use of the DSVE in two demonstrations is then discussed, followed by conclusions.

LITERATURE REVIEW

The field of virtual systems is a relatively new field of study, since the hardware and software has only been available during the last ten years. For this reason, the literature is

limited, but there are several important areas of research that have emerged.

Waurzyniak [1] outlines important advantages to virtual modeling and calls for better performing, less expensive virtual prototyping systems. Important advantages outlined include the elimination of physical prototypes, which can save automakers and aircraft suppliers millions of dollars per year. Another advantage is the potential to lessen the time needed to bring new products to market.

Gomes de Sa [2] provides some important definitions of virtual prototyping. Virtual prototyping is the application of virtual reality for prototyping. Another aspect of virtual design and prototyping is the promise of economic savings. Digital mock-ups are a realistic computer simulation of a product with the capability of all required functionality from design/engineering, manufacturing, product service environment, maintenance, and product recycling. Digital mock-ups are used as a platform for product and process development, for communication, and making decisions from a first conceptual layout. Werkhoven [3], Boudreaux [4], and others have studied virtual environments for designing ships. Werkhoven lists areas in which the use of virtual environments has proven to be worth the cost.

Balaguer describes a pilot project called Virtual Environment Navigation in the Underground Sites (VENUS) for virtual prototyping. VENUS is composed of four applications. They are virtual prototyping, networked design integration, territory impact study, and assembly planning and control. Balaguer [5] points out that binocular perception allows for better understanding of the complex spatial relationships between parts of a prototype. He comments on the current capabilities of today's CAD tools as being too limited to allow interactive navigation. In addition to limited navigation capabilities, eventual design errors are difficult to isolate.

Jayaram et al. [6] describes a virtual reality based engineering application that allows engineers to plan, evaluate, and verify the assembly of mechanical systems called the Virtual Assembly Design Environment (VADE). VADE represents collaboration between the University of Washington and the National Institute of Standards and Technology (NIST). The virtual environment within VADE presents the user with an assembly scene. The tools used in the assembly process, such as screwdriver and wrench, are located where they would be in a real assembly facility. These locations are user defined. VADE uses a virtual hand to facilitate assembly and interaction with the system is accomplished with a CyberGlove.

Arangarasan and Gadh [7] describe a system called Detailed Virtual Design System (DVDS) under development for detailed shape modeling in a multi-modal, multi-sensory virtual environment. The DVDS provides an intuitive and natural way for mechanical design using hand motion and voice commands. Work with DVDS has focused on the use of

data gloves and voice commands, and the research effort of Aranigarasan and Gadh has placed emphasis on collaboration of design teams over a network where designers are in separate locations.

In earlier work conducted at the Navy Research Laboratory, Summers et al. [8] discussed a feature based virtual system. The feature-based system is a direct predecessor of the work reported in this paper, and many of the research goals expressed in the earlier paper have been realized through the DSVE system.

Although the VADE, VENUS, and DVDS projects represent important new applications of virtual environments, it is apparent that experimentation in the use of virtual systems for engineering design purposes has been significantly limited. This brief review has summarized work in virtual prototyping, applications of virtual environments to ship design, and early systems for design, development, and analysis. As one such system, the Design Synthesis Virtual Environment research effort reported here, adds to the literature on the use of virtual environments for engineering design.

HARDWARE AND SOFTWARE

The demands placed on the computer and graphics subsystems for a virtual environment are substantial due to the higher numbers of polygons to render in real-time and the higher frame rates involved to support stereoscopic vision. A magnetic tracking system is needed to facilitate gestural input, object picking in three dimensions, and correct user-perspective viewing. These processes add additional tasks to the computer hardware, requiring significant computational power.

The high fidelity graphics are generated by an SGI Onyx 2 with two graphic pipes, and four raster managers. The software employed includes the Irix Version 6.5 Operating system, SGI Performer Version 2.2 Graphics library, and OpenGL. Additionally, the Virtual Reality Peripheral Network software, described below, is used to control the tracking and interface device systems. The display device is the GROTTTO, installed at the Naval Research Laboratory (NRL).

The GROTTTO (Graphical Room for Orientation, Training, and Tactical Observation) is a Surround-Screen Visualization Environment (SSVR™) system developed by Mechdyne Corporation. The GROTTTO uses folded optics to project images from CRT projectors onto translucent wall and white floor surfaces. The images are produced on left, front, and right walls by back projection and on the floor by direct projection. Crystal Eye shutter glasses are used to produce a stereoscopic view. The user's position within the GROTTTO is tracked by an Ascension Flock of Birds (FOB) magnetic tracking system. A sensor is attached to the user's eyewear and a sensor is attached the flightstick.

The flightstick, shown as Figure 1, is the primary means of interacting with the immersive virtual reality system. It

consists of a PC computer joystick modified by the addition of the magnetic tracker as well as re-wiring the four buttons to interface via an Immersion Technologies I-box. Logically, the flightstick is a six degree-of-freedom tracked device with four buttons.

The I-box allows connection of up to eight input devices, four digital and four analog, to any computer with a serial port. The host computer accesses the I-box through standard serial communications.

The tracking system and I-box interfaces employ the Virtual Reality Peripheral Network (VRPN) client-server software, provided by the University of North Carolina, Chapel Hill with funding from the National Science Foundation.

A user operates the CAD system while standing inside the GROTTTO. Although the primary interaction uses the flightstick, the keyboard and mouse are still needed to communicate with the computer for some activities. Leaving the GROTTTO to access the keyboard is an inefficient and unproductive action. A lightweight, portable stand called the pulpit is constructed of PVC pipe and plywood to support the keyboard and mouse inside the GROTTTO.

OVERVIEW OF DSVE OPERATION

The DSVE software functions much like ordinary CAD/CAE software, with the addition that it works in a completely immersive virtual environment. For the system outlined in this paper, the user has a three-dimensional environment rather than the two-dimensional environment of a typical CAD/CAE system. In this three-dimensional environment, human-computer interaction is accomplished using the flightstick for most user actions. Most major functions, such as navigating the scene graph, creating, modifying and deleting geometry, and selecting tools are achieved by gesture alone using the flightstick.

It is noteworthy that with respect to other multi-wall virtual reality applications, DSVE represents a departure from current conventions. In most applications, objects (and the virtual environment itself) are projected so that the user views himself or herself as being in a world that extends *beyond* the walls of the display device. In the best systems, the user is induced to imagine that the 'landscape' extends infinitely in every direction. In contrast, in the DSVE synthesized geometry is suspended in mid-air, approximately one meter in *front* of the GROTTTO's front wall. This creates a "design volume" that exists roughly in the middle of the GROTTTO. The user creates, walks around, and interacts with geometry displayed within this volume. Because of the GROTTTO's layout, the front wall and floor are the primary display surfaces. However, the right and left GROTTTO walls are also used to support interaction.

The left wall of the GROTTTO contains a calculator used to assist the engineer in the development of a design. The calculator uses the XCALC utility commonly available in the

X Windows environment. Other interaction is also available on the left wall of the GROTTTO through an open Irix window, allowing the designer communication with the computer system. Figure 2 shows the left wall of the GROTTTO with the pulpit, flightstick, and shutter glasses.

The DSVE implements a tool handle/tip metaphor for interaction. The flightstick represents a tool handle, into which the user may plug tool tips to accomplish various tasks. Interaction is facilitated through use of a ray for selection of tools or objects in the immersive environment. Tracking algorithms cause the ray to appear to the user to emanate from the flightstick and to point in the proper direction at all times.

On the GROTTTO right wall is a three-dimensional tool cabinet for nine tool tips used for interaction with the design space. Each tool tip is represented by a three-dimensional icon and implements one form of interaction. For example, the rotate tool tip is used to rotate geometry about an axis, and the sphere tool tip is used for generation of spherical primitives. In each case, appropriate tool tips are removed from the cabinet for use with the tool handle. When changing tips, visual feedback is provided by changing the graphical representation of the tool tip in the virtual environment. Pressing a button (usually the Trigger) on the tool handle activates the tip function. Figure 3 shows a view of the tool cabinet from inside the GROTTTO, and Table 1 describes tool tip functions.

The current version of the DSVE provides three major tool tips to choose from: Select, Create, and Modify. The Select tool tip is represented by a red pointer and is used to select tools from the cabinet and geometry from the virtual workspace. The Create tool tip is used to create and place geometry in the design environment. When the Create tip is active, a small representation of the current geometric primitive appears at the end of the pointer. The Modify tool tip is represented by a hand with a green pointer and is used to change existing geometry by scaling, rotating, or translating. Once the Modify tip is active, a letter appears behind the hand to indicate the function (scale, rotate, translate) that is current.

Figure 4 shows the red pointer ray, primarily used for selection of objects from the tool cabinet. To select an object, the user points at it with the flightstick and pulls the Trigger. For example if the user wishes to place a sphere in the workspace, the user would use the Selector tip to point at the sphere icon in the cabinet. Pressing the trigger places the Create tip on the tool handle, and prepares it for use with the sphere geometric primitive as shown in Figure 5.

Changing the tool tip can also be accomplished by depressing the fire button on the flightstick. Figure 6 shows the result of selecting the translate tool tip. Note that a yellow capital "T" behind the hand provides visual feedback to the change in function.

In the current version, synthesis of geometry is accomplished using geometric primitives. The primitives currently available include boxes, cylinders, cones, spheres, an

annulus referred to as a pipe, and NURBS surfaces. (The pipe and NURBS surfaces are not shown in this paper). A primitive is selected for use, and the system automatically gives the primitive a unique name, generates the primitive with unit dimensions, and places the primitive at the origin of the axis system. The primitive can then be manipulated by changing its dimensions through scaling, by changing its orientation through rotation, and by translating it. Manipulations are controlled by user gestures using the flightstick. By using the scale, rotate, and translate functions geometry is sized and placed in desired configurations by simple gestures.

Selection of primitives for use with the Create tip is shown in Figure 7. In addition to selection via the tool cabinet, the user can also cycle among the available geometric primitives by pressing the left flightstick button. When the desired primitive is shown, the user depresses the flightstick trigger to place a copy of the current primitive at the origin, ready for modification.

The Modify tool tip is used to change existing geometry in the design volume. Modifications consist of scaling, rotation, and translation. Tool tip selection is normally accomplished by interaction with the tool cabinet. These choices may be also cycled using the flightstick left button in a manner similar to that above. Feedback is provided in the form of a large letter corresponding to the action: T is for translate, R is for rotate, and S for scale. Figures 6 and 8 illustrate this process.

Synthesis of geometry begins by selecting a geometric primitive from the tool cabinet. With the desired primitive shown at the end of the Create tip, the user presses the flightstick trigger. The system then automatically gives the primitive a unique name, generates the primitive with unit dimensions, and places it at the origin of the axis system. Once located at the origin, primitives can then be manipulated by changing dimensions through scaling, changing orientation through rotation, and by translation in each dimension. Figures 9 through 11 show selecting translate, rotate, and scale functions, respectively, in the tool cabinet.

All modifications are made through user gestures. At the start of a gesture, the flightstick position coordinates and orientation quaternion are read from the magnetic tracking and stored as the "start." As the flightstick is moved, the DSVE constantly updates the gesture vector that is computed based on the difference in position and orientation between the current flightstick position and that at the start of the gesture, using tracker data.

When scaling, the direction of the gesture indicates the direction of the scaling effect, and the magnitude of the gesture is used to determine the amount of scaling applied. To scale a component, the sequence is: a) the user selects the Modify tip and chooses the scale function; b) the user points at the component and pulls the trigger, thereby starting the gesture; c) the user moves the flightstick in the direction and magnitude of the desired scaling during which the component is re-scaled in real time to match the user's input; and d) upon

reaching the desired result, the user releases the trigger thereby completing the scale operation.

When rotating, it is the change in orientation of the flightstick from the start of the gesture that is used to modify the geometry. To rotate a component, the user: a) selects the Modify tip and chooses the rotate function; b) the user points at the component and pulls the trigger, thereby starting the gesture; c) the user twists the flightstick in the direction of the desired rotation during which the component is rotated in real time to match the user's input; and d) upon reaching the desired result, the user releases the trigger thereby completing the operation. Rotation was originally developed to provide rotation about one of the axes present in the DSVE. As an alternate, rotation about an object's center was developed, and research is continuing with regard to the best user interface for the rotate function.

Translation takes place in a similar manner to scaling, except that the gesture moves the geometry rather than scales it. An 'Undo' function is available to reverse the last modification.

Figures 12 and 13 show alteration of a box by scaling along each of two axes, while Figure 14 shows modifications to a cone. In each case, the manipulations are controlled by user gestures using the flightstick.

As action to create and modify geometry, primitives are selected and placed at the origin. The scale, translate, and rotate functions are then applied to geometric primitives. By using the scale, rotate, and translate functions geometry can be sized and placed in desired configurations by simple gestures. Figures 15, 16, and 17, show translation of a box and a cylinder by gestures. Further details can be found in Maxwell's [9] work.

For the research reported in this paper, the flightstick is used as the principle means of interaction. However, the tool handle and tool tip metaphor were developed purposefully and specifically to allow rapid and easy conversion to other interface devices such as gloves, haptic feedback devices, and voice. The software presently has provisions for future experimentation, but the work reported upon in this paper employs the flightstick as the principal means of interaction for the synthesis of geometry.

Once significant three-dimensional geometry is synthesized, it can be saved in a file. For this action, the keyboard on the pulpit is used. As an action that restores geometry from a saved file, the load function is also available at the keyboard to restore three-dimensional geometry from a file.

Storage of geometric data currently does not involve solid modeling. Although the research team has recent relevant experience with ACIS solid modeling (see [10]), costly licensing issues cause the inclusion of solid modeling methods to be deferred to future research. Because this paper principally focuses on the use of an immersive environment for geometric synthesis, provisions were made for future use of

solid modeling, and the principle research thrust remains investigation of the synthesis of designs in a virtual environment.

In addition to keyboard action for saving and recalling geometry, feature information related to the geometry, such as tolerances, can be entered and saved for each unit of geometry. This feature based information storage and recall provides a means of data management that would be useful for analysis, manufacturing, and other product realization purposes.

DEMONSTRATIONS

To illustrate the capabilities of the DSVE, experiments employing the DSVE to solve mechanical design problems were conducted. Two demonstrations were undertaken to gain experience and to exercise DSVE features. The first demonstration was provided by an experienced naval architect and represented an actual ship geometric design problem. The second illustrative problem was more generic and provided additional experiential data regarding system capabilities and limitations.

A Ship Design Problem

Equipment located on a specific ship class has experienced significant problems due to the geometric arrangement of components and the mechanical relationships between power transmission and kinematic machine requirements. As a first example, the problem in ship design was undertaken with the DSVE, and the DSVE proved helpful in the construction of a geometric model and analysis of the mechanical arrangement for this mechanical system.

The Universal Joint Problem

The second illustrative problem is a relatively generic mechanical design example based on a common universal joint. The geometric synthesis and modeling of the universal joint is a well-known mechanical problem to which many can easily relate. For this reason, work with the universal joint is discussed in detail.

As an illustration of this capability, the geometry of a universal joint is synthesized starting with a box. At inception, the box has unit dimensions and exists at the origin. However, it is reshaped by scaling along an axis. Also, the box is repositioned by translation as shown in Figure 18. The letter "T" is displayed to signal the translation operation.

As the design synthesis process continues, geometric primitives are moved or shapes are altered with gestures. This task is done by selection using the red pointer. Upon selection, the primitive is moved or altered using gestures as needed using the scale, translate, and rotate capabilities. As the synthesis process continues, additional geometry is added. In addition to the box, a cylinder is generated, and the cylinder is scaled and translated to become part of the universal joint, shown in Figure 19. This activity occurs through gestures with

the flightstick. Additional primitives are added as the design synthesis process continues, as seen in Figure 20. As an illustration of this capability, a more complete universal joint model is seen in Figure 21.

As a three-dimensional immersive model, examination and review of this geometry from any angle or perspective is possible. The user can even view an object from inside that object. Because the viewpoint from the pages of this paper is only two-dimensional, one cannot experience this effect, but the user with shutter glasses does have a fully immersive, three-dimensional experience. Review of the synthesized geometry in the DSVE is one of the greatest reasons for the use of an immersive design paradigm. Figures 22 through 24 show alternate views of the universal joint, with each view rendered in real-time by the Onyx 2 computer based on the user's position. As a result, the designer can simply move about the GROTTTO to examine the product from any perspective.

By developing geometry for a mechanical design in the DSVE, it is believed that the engineer can experience and review his or her designs in new ways. This spatial feedback allows more rapid and effective generation of a higher quality design, and holds the possibility of giving new tools to engineers that design and construct complex mechanical systems.

OBSERVATIONS AND CONCLUSIONS

Experience with the DSVE provides demonstration of three dimensional design synthesis using a flightstick for gestural interaction. The DSVE has the ability to create geometric primitives and to modify them to create more complex pieces of geometry. The DSVE is fully immersive utilizing real-time stereographic rendering and magnetic tracking.

Additionally, the pulpit works well to provide keyboard input while inside the GROTTTO. However, the need for keyboard input is greatly diminished while inside the DSVE, because interaction with the design environment occurs through gestural activity.

Gesture interaction with the system is inexact. This is consistent with conclusions reached by Vance, Butler, and Ebbesmeyer [11]. Future research with this system should provide further opportunities for experimentation. Currently, inexactness of the gesture input is solved by keyboard input. Gesture input is not meant to replace the keyboard in a CAD/CAE system, but instead to provide an easy to use 3D interface with a CAD/CAE system.

Tool tip navigation is cumbersome without the addition of visual cues. Visual feedback in DSVE is essential for the typical user. Although flightstick button equivalents are available for most of the icons in the tool cabinet, the cognitive load associated with recognizing which buttons to push on the flightstick and at what time to push them is too much for some

users. Also, significant cognitive load is placed on the user to maintain geometric consistency within the DSVE.

Viewing complex mechanical models inside the DSVE provides a new and unique perspective that captivates all that view it. The universal joint illustration provided excellent demonstration material.

The development of the DSVE and its demonstration on two problems in mechanical design represents experimentation with a new technology for generation of designs by engineers. It provides an initial but limited experience from which further research can be conducted. It is argued that the use of a three dimensional interface, such as the system provided by the DSVE is superior to the user interface in a conventional non-immersive CAD/CAE systems. The DSVE system permits the designer to view his or her design in an immersive environment giving a much richer quality of visual feedback during the design synthesis process. The gestural interface provides a new means of interaction in which natural human movement in the immersive environment is substituted for multiple keystrokes and 2D mouse movement. Although objective statistical data is not yet available to quantitatively substantiate the benefits of these methods, experience with the initial demonstration of the DSVE system leads authors to assert that the DSVE technology holds significant promise.

With further research and study, the human computer interaction issues can be better understood, and it is believed that with this further study and development, the DSVE approach to design of mechanical systems could revolutionize the manner in which design is conducted. Through this revolution in technology, engineers are offered a superior means of designing ships, aircraft, and other complex mechanical products. The result is better quality, improved performance, and a substantial increase in the responsiveness of the engineering design function to the needs of our world.

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Table 1 – Tool Tip Names and Associated Functions

Tool Tip	Function
Scale	Scale selected geometry.
Rotate	Rotate selected geometry.
Translate	Translate selected geometry.
Sphere	Create a sphere in the design volume.
Cone	Create a cone in the design volume.
Cube	Create a cube in the design volume.
Cylinder	Create a cylinder in the design volume.
Red Pointer	Enable use of the red pointer.

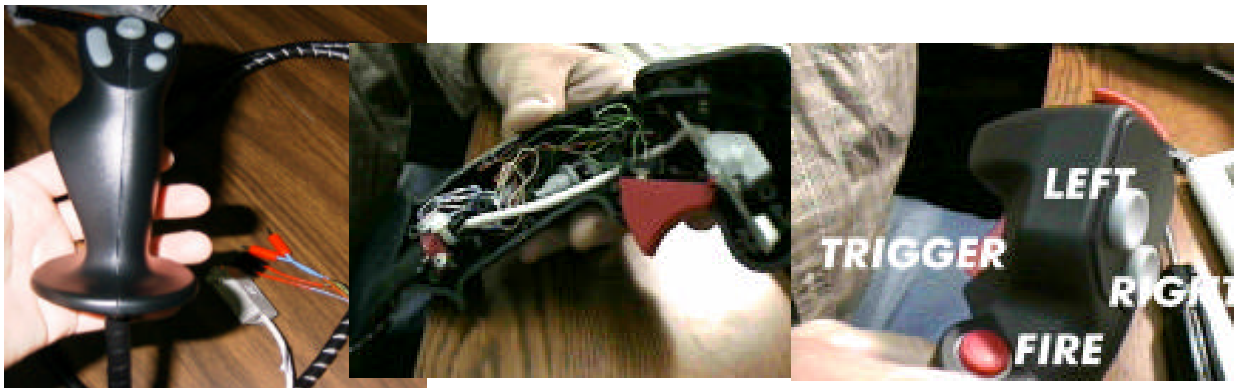


Figure 1 – Dissection of the Flight Stick

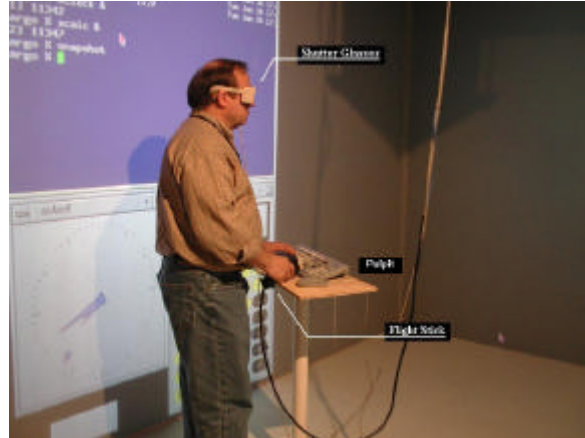


Figure 2 – The Pulpit and Left Wall of the GROTTTO

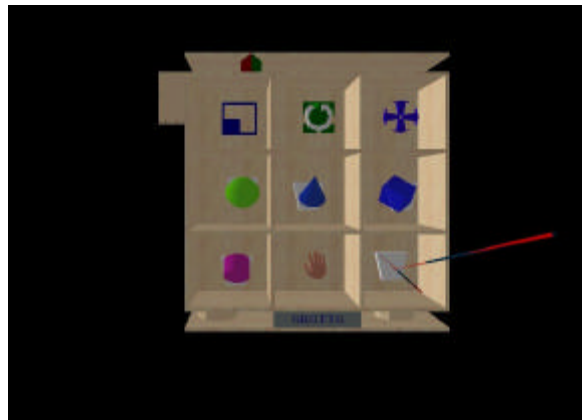


Figure 3 – The Cabinet of Tools

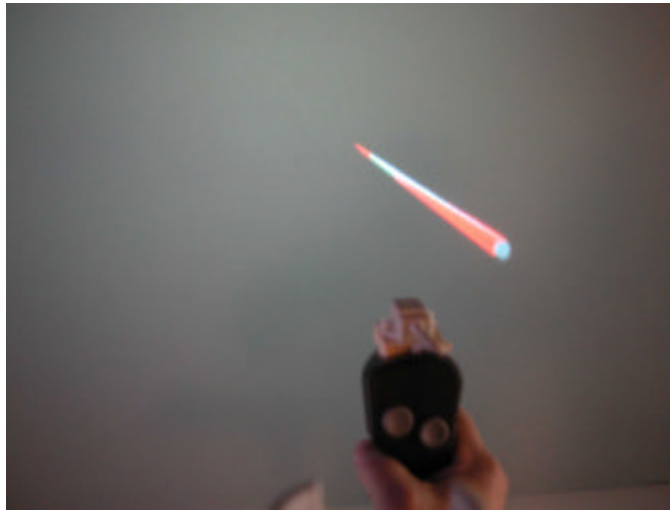


Figure 4 – The Red Pointer

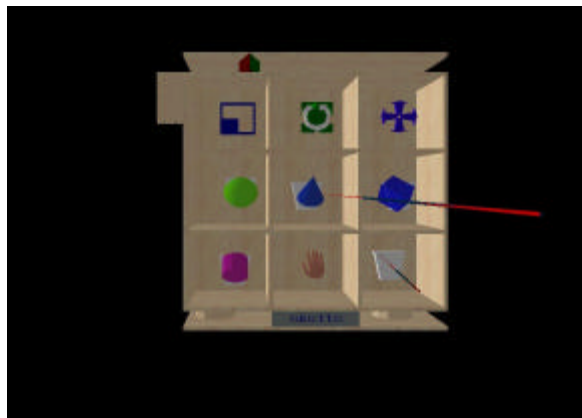


Figure 5 – Selection of the Sphere Primitive from the Tool Cabinet

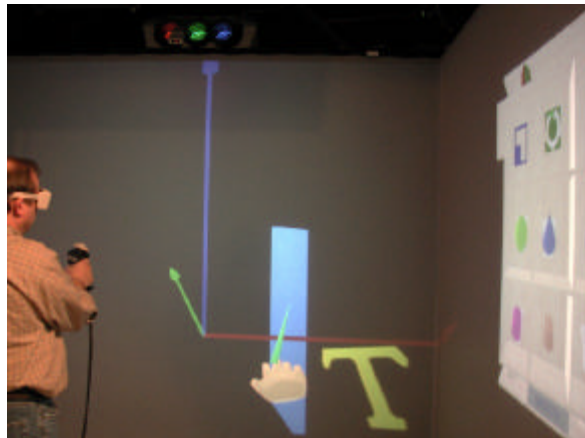


Figure 6 – Tool Tip Change to the Translate Function

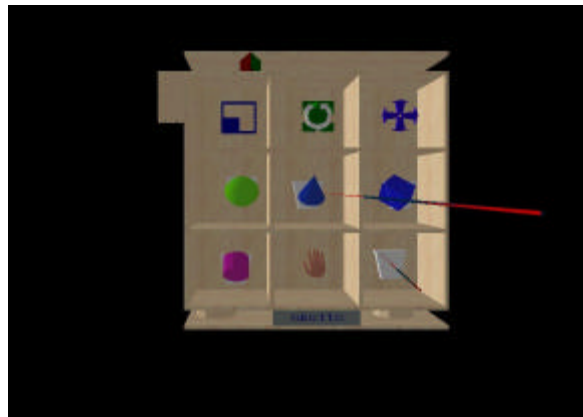


Figure 7 – Selection of a Cone

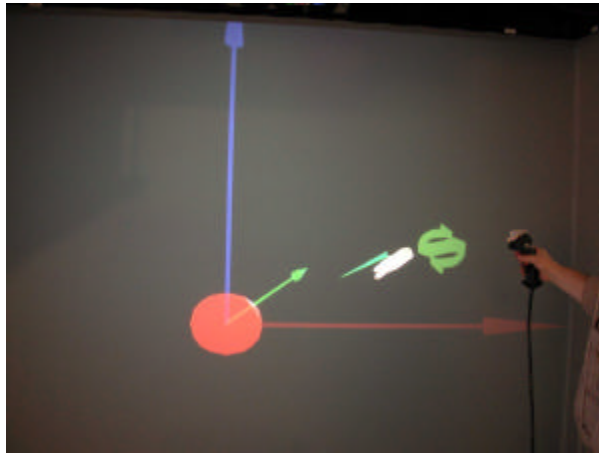


Figure 8 – Changing the Tool Tip to Scale a Sphere

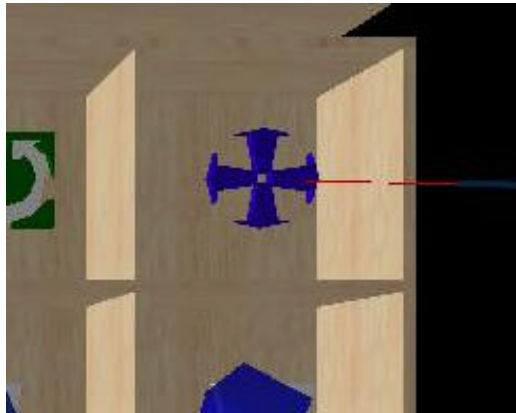


Figure 9 – Modify Tool Tip Set for Translating Operations

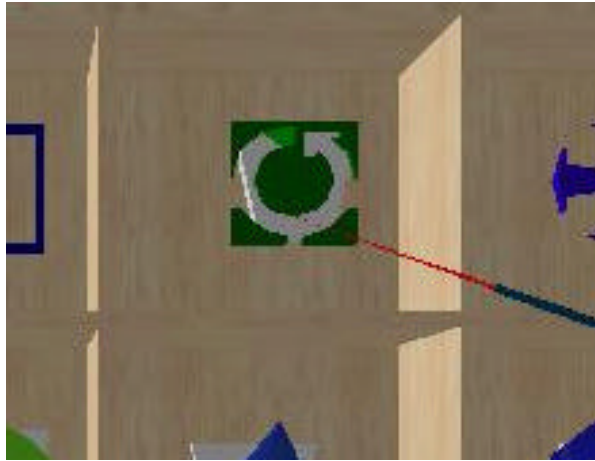


Figure 10 – Modify Tool Tip Set for Rotating Operations

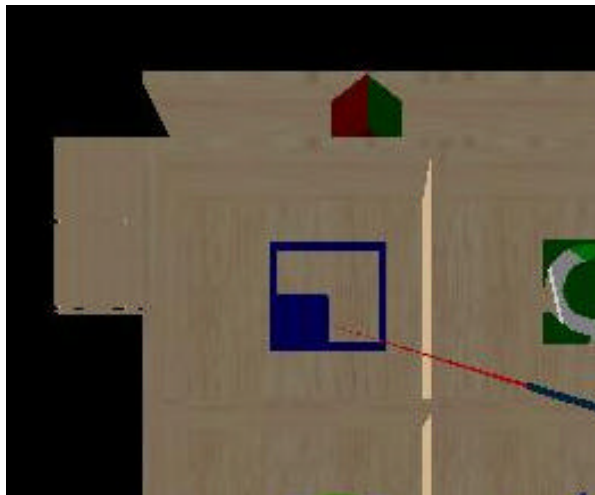


Figure 11 – Modify Tool Tip Set for Scaling Operations

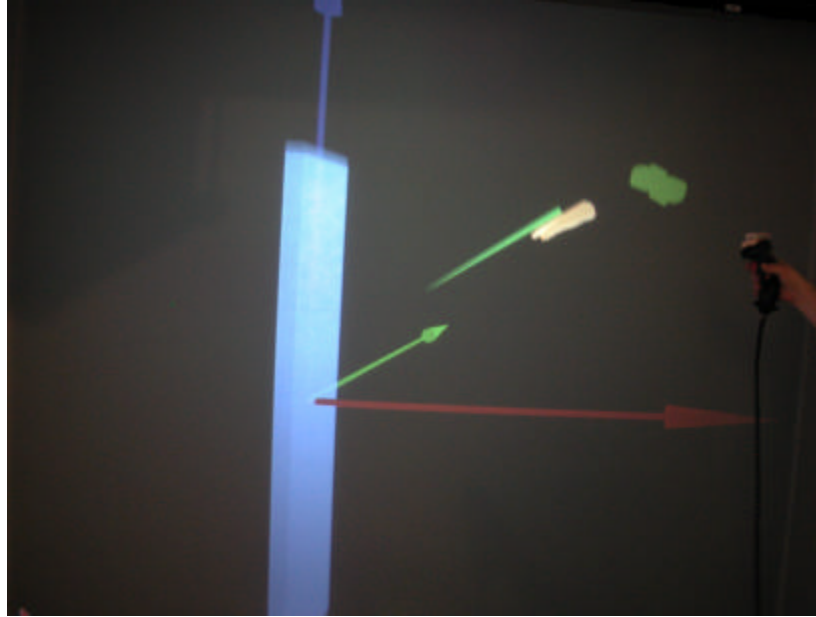


Figure 12 – Scaling of a Box Along the First Axis

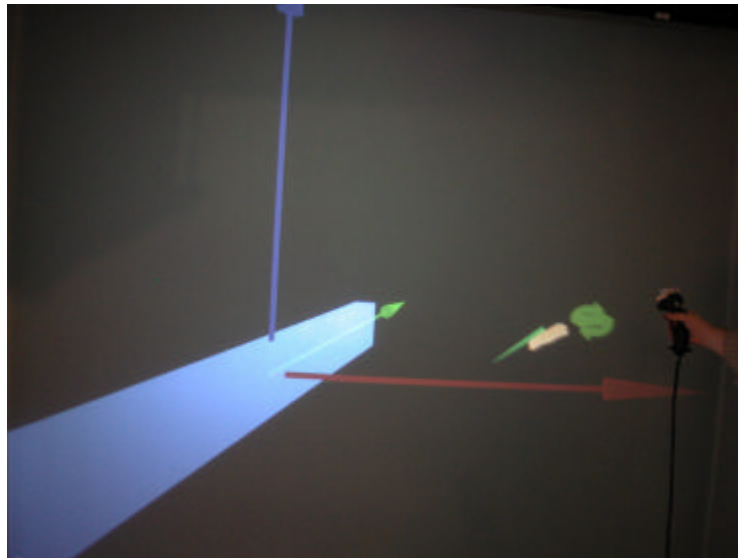


Figure 13 – Scaling of a Box Along the Second Axis

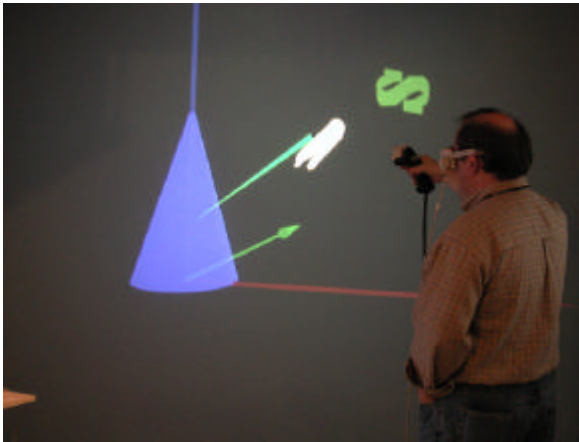


Figure 14 – Scaling Operations on a Cone

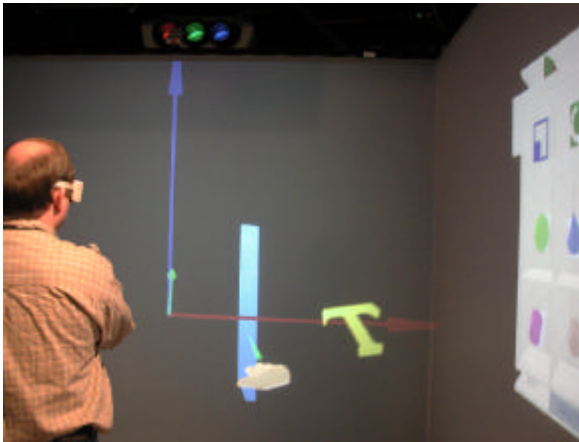


Figure 15 – Translation of a Box

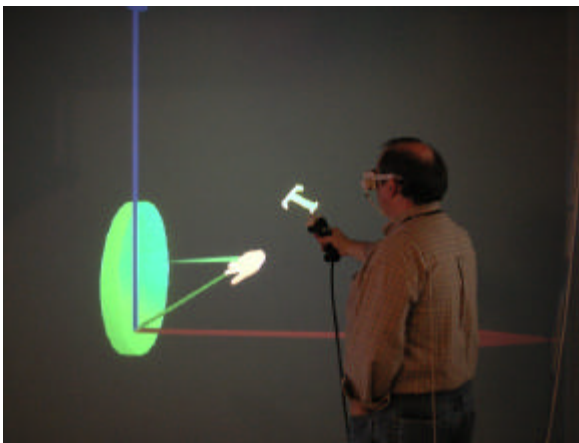


Figure 16 – Translation of a Cylinder

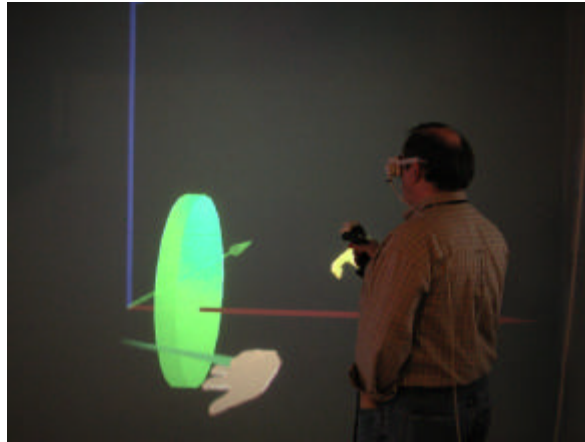


Figure 17 – Further Translation of a Cylinder



Figure 18 – Repositioning a Box

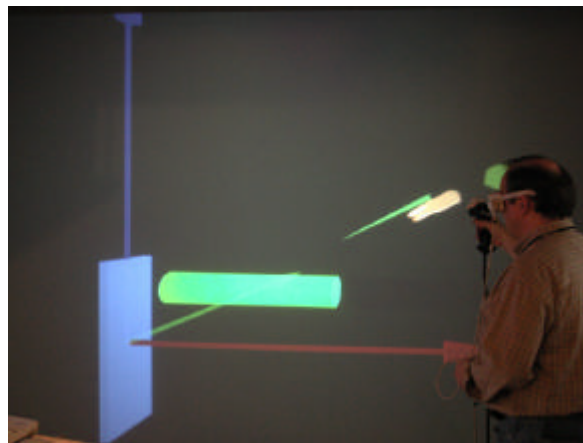


Figure 19 – Adding a Cylinder to the Design

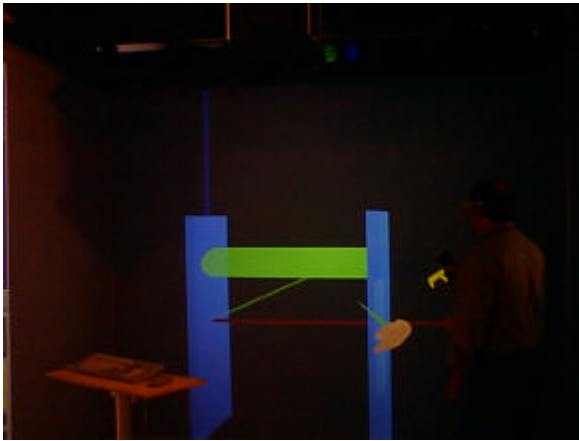


Figure 20 – Adding Another Box to the Design



Figure 21 – A Completed Geometric Model

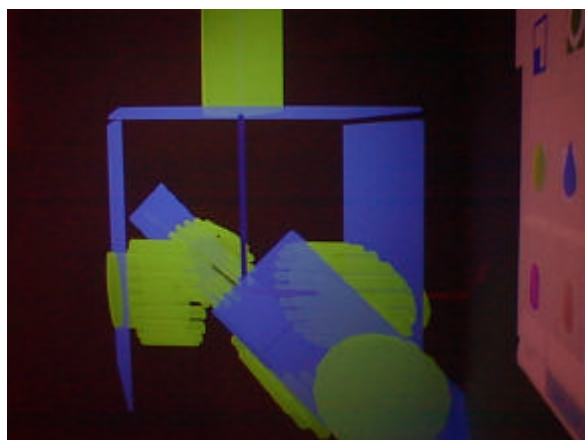


Figure 22 – Viewing the Universal Joint from a Second Perspective

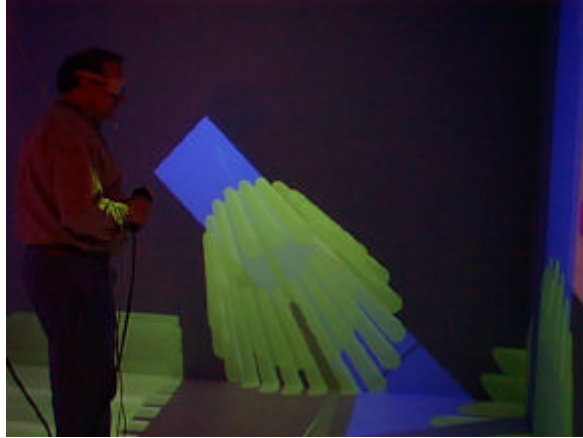


Figure 23 – Viewing the Universal Joint from a Third Perspective

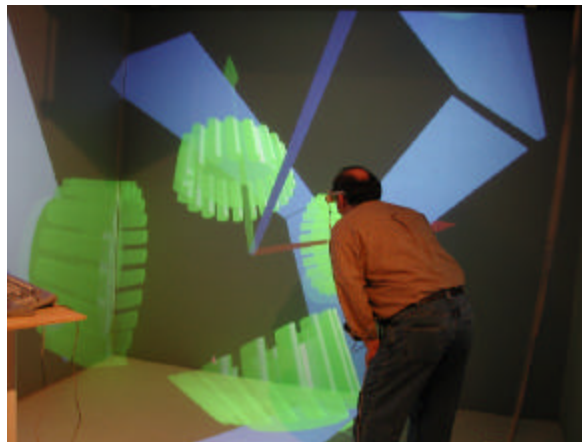


Figure 24 – Viewing the Universal Joint from a Fourth Perspective

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